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FLIGHT INVESTIGATION OF STABILITY AND CONTROL CHARACTERISTICS OF A 1/8-SCALE MODEL OF A TILT-WING VERTICAL-TAKE-OFF-AND-LANDING AIRPLANE

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SUMMARY

An experimental investigation has been conducted to determine the dynamic stability and control characteristics of a tilt-wing vertical-take-off-and-landing airplane with the use of a remotely controlled 1/8-scale free-flight model. The model had a wing which could be tilted up to an incidence angle of approximately 90° for vertical take-off and landing. The investigation consisted of hovering flights in still air, vertical take-offs and landings, and slow constant-altitude transitions from hovering to forward flight.

The stability and control of the model were found to be generally satisfactory with the following exceptions. In hovering flight, the model had unstable pitching and rolling oscillations. The pitching oscillation could be controlled adequately even if the model were allowed to build up to an appreciable amplitude. If the rolling oscillation were allowed to build up to a modest amplitude, however, the oscillation could not always be controlled with the amount of control power proposed for the full-scale airplane. In transition flight and at angles of wing incidence somewhere between 90° and 60°, the model experienced large nose-up pitching moments which severely limited the rearward center-of-gravity locations that could be used.

INTRODUCTION

An investigation has been conducted to determine the stability and control characteristics of a 1/8-scale flying model of the Hiller X-18 airplane. Conventional wind-tunnel force tests were made of the model, and the results are presented in reference 1. Flight tests were also made and are reported herein. The flight tests consisted of slow constant-altitude transitions from hovering to forward flight in the Langley full-scale tunnel, hovering flights near the ground and well above the ground, and vertical take-offs and landings. The results were obtained mainly from pilots' observations and from studies of motion-picture records of the flights.

APPARATUS AND TESTS

Model

A photograph of the 1/8-scale model of the Hiller X-18 airplane
during a transition flight in the Langley full-scale tunnel is shown L
in figure 1, and a three-view sketch showing some of the more important 6
dimensions is shown in figure 2. Table I gives the scaled-up geometric 2
characteristics of the model. The variations of the moments of inertia 5
of the model with wing incidence are shown in figure 3. In table II the scaled-up moments of inertia of the model are compared with the full-scale airplane moments of inertia at a wing incidence of 90°. In figure 4 the variation of the center of gravity of the model with wing incidence is shown and is compared with the values for the airplane in the light-weight condition of 27,278 pounds and the heavyweight condition of 33,000 pounds. The model had two six-blade dual-rotating propellers that were powered by 5-horsepower electric motors which were not interconnected. The speeds of the motors were changed together to vary the thrust of the propellers.

The wing was pivoted at the 34.8-percent-chord station 0.46 inch below the lower surface of the wing and could be rotated between incidences of $4\frac{1}{2}^{\circ}$ and $94\frac{1}{2}^{\circ}$ during flight by means of an electric actuator. The wing span was changed from 6 feet to 7.5 feet by the addition of wing-tip extensions. These spans of 6 and 7.5 feet scale-up to 48 feet and 60 feet, respectively, on the full-scale airplane and are called the short wing and long wing, respectively, herein. The model had conventional aileron, rudder, and elevator controls for forward flight. For hovering flight the ailerons provided yaw control, a compressed-air jet at the tail provided pitch control, and differential total pitch of the rear elements of the dual-rotation propellers provided roll control.

The controls were deflected by flicker-type (full-on or full-off) pneumatic actuators which were remotely operated by the pilots by means of solenoid-operated valves. All control actuators, with the exception of the control actuator on the pitch jet, were equipped with integrating-type trimmers which trimmed the controls a small amount each time a control was applied. With actuators of this type, a model becomes accurately trimmed after flying a short time in a given flight condition. The pitch-control actuator on the tail jet had a motor-driven trimmer which was operated by the pitch-control pilot from one of two control sticks so that the tail jet could be rapidly trimmed independently of the flicker control deflections.

Test Equipment and Setup

The test setup used in the transition flight tests in the Langley full-scale tunnel and in the hovering flight tests was essentially the same as is illustrated by the sketch of the full-scale-tunnel setup shown in figure 5. The power for the main propulsion motors, the wing-tilting motor, and electric control solenoids was supplied through wires, and the air for the control actuators and the tail control jet was supplied through plastic tubes. These wires and tubes were suspended from above and taped to a safety cable (1/16-inch braided aircraft cable) from a point about 15 feet above the model down to the model itself. The safety cable, which was attached to the fuselage near the center of gravity, was used to prevent crashes in the event of a power or control failure or in the event that the pilots lost control of the model. During flight the cable was kept slack so that it did not appreciably influence the motions of the model. Separate pilots were used to control the model in pitch, roll, and yaw since it had previously been found that if a single pilot operates all three controls, he is so busy controlling the model that he has difficulty in ascertaining the true stability and control characteristics of the model about its various axes. The take-off, landing, hovering, and oscillation tests were made with an almost identical setup in a large building that provided protection from inclement weather and the random effects of outside air currents.

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Tests

The investigation reported herein consisted entirely of flight tests. The results were mainly qualitative and consisted of pilots' observations and opinions of the behavior of the model. Motion-picture records were made of all the flights which were subsequently studied in detail.

Hovering flight tests were made with the short wing to determine the basic stability and control characteristics of the model in still air at a height of 15 to 20 feet above the ground to eliminate any possible effect of ground proximity. Detailed studies of the stability and control characteristics were made for the case in which the center of gravity was located directly below the wing pivot. In these tests the uncontrolled pitching and rolling motions and the ease with which these motions could be stopped after they had been allowed to develop were also studied. The model was also flown in controlled flight over a range of center-of-gravity positions in an attempt to establish an allowable center-of-gravity range for hovering flight.

Hovering flight tests were also made near the ground to determine the effect of proximity of the ground on the flight behavior of the model. These tests were made with the wheels from about 2 inches to 10 inches above the ground.

Take-off and landing tests were made with the short wing for the condition with the center of gravity located at 2 percent chord forward of the wing pivot. The take-off tests were made by rapidly increasing the power to the propellers until the model rose from the ground. The power operator then adjusted the power for hovering and the model was stabilized at various heights above the ground. For the landing tests, the power operator reduced the power in such a manner that the model descended slowly until the landing gear was about 6 inches above the ground. At this point the power was reduced quickly and the model settled to the ground on the landing gear.

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Transition tests representing slow constant-altitude transitions were made in order to study the stability and control characteristics of the model and to determine the effects of fuselage attitude, tail-jet force, center-of-gravity position, and wing span (short and long wing configurations). The transition flight tests were made for a range of center-of-gravity locations from 7 percent chord forward of the wing pivot to 9 percent chord behind the wing pivot. The center-of-gravity locations are referred to in the discussion of the flight tests in terms of the location when the wing was in a hovering flight position of $94\frac{1}{2}^{\circ}$ wing incidence. As the wing rotated to $4\frac{1}{2}^{\circ}$ incidence, the center of gravity of the model moved forward and down approximately the same amount as that of the airplane, as can be seen in figure 4.

The transition tests were made in the Langley full-scale tunnel by using the test technique illustrated in figure 5 by starting with the model hovering in the test section at zero airspeed. As the airspeed was increased by the tunnel operator, the wing-tilt operator gradually reduced the wing incidence to maintain the model location in the test section during the transition. These flights covered a speed range from 0 to about 45 knots. Since the model was a 1/8-scale model of the full-scale airplane, the corresponding scaled-up airspeeds would be $\sqrt{8}$ (or 2.83) times those of the model. Small adjustments or corrections in the tunnel airspeed could not be made readily; the pitch pilot, wing-tilt operator, and power operator, therefore, had continually to make adjustments to hold the model in the center of the test section. Flights were also made in which the airspeed was held constant at intermediate speeds of 22, 29, 36, and 44 knots so that the stability and control characteristics at constant speeds could be studied.

A few flights were also made in the Langley full-scale tunnel in order to determine the stability and control characteristics of the model in rearward and sideward flight. In all of these tests the wing incidence was set at $94\frac{1}{2}^{\circ}$.

In the detailed hovering tests, the maximum up or down force available from the pitch jet was limited to ± 4.2 percent of the model weight. A limited number of hovering flight tests were made with a pitch-jet force of ± 7.5 percent of the model weight in order to study the ability of the pilot to stop a developed pitching oscillation. Most of the transition tests were made with a maximum pitch-jet force of ± 7.5 percent of the model weight, although a few transition tests were made with a pitch-jet thrust of ± 9.1 percent of the model weight, which corresponded to the sea-level condition for the airplane. The elevator could be switched into and out of the pitch-control circuit but usually operated during the entire transition flight. The elevator deflection used was $\pm 20^{\circ}$.

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Yaw control in hovering and low-speed flight was obtained by deflecting the ailerons differentially $\pm 30^{\circ}$ (each aileron). At a speed of about 13 knots the ailerons were switched out of the yaw-control circuit and the yaw pilot generally stopped giving control since the model became so directionally stable that no yaw control was required.

Roll control in hovering and low-speed flight was obtained by varying the pitch of each of the rear elements of the dual-rotation propellers differentially $\pm 1\frac{1}{2}^{\circ}$. At a speed of about 24 knots, the differential-propeller-pitch control was switched out of the roll-control circuit and the ailerons and rudder were switched in, to be used together for roll control for the remainder of the flight. The rudder deflection used was $\pm 20^{\circ}$.

RESULTS AND DISCUSSION

A motion-picture film supplement has been prepared and is available on loan. A request card form and a description of the film will be found at the back of this paper on the page immediately preceding the abstract and index pages.

The overall impression of the pilots after flying the model throughout the test program was that the stability and control characteristics were generally acceptable and the model could be flown with reasonable ease and safety without the use of artificial stabilization. The pilots believed, however, that when the amount of lateral control currently used on the full-scale airplane (as given in the discussion of rolling motions in the section entitled "Hovering Flight") was simulated on the model, the control was weaker than was desired to cope with the unstable rolling oscillation encountered in hovering flight.

Hovering Flight

Pitching motions.- The flight tests showed that in hovering flight the model had an unstable pitching oscillation with a period of about 4.6 seconds and a time to double the amplitude of about 1.1 seconds. Figure 6(a) shows time histories of these unstable oscillations in which the pilot held the stick fixed in a neutral position and allowed the oscillation to build up until the model had to be retrieved by the safety cable. With a pitch-jet reaction-control force of ±7.5 percent of the model weight, the pilot could stop this oscillation easily, even after the oscillation had been allowed to build up to a large amplitude, as illustrated by the time histories of figure 6(b). This amount of pitch-jet force represented that available for the full-scale airplane when hovering at its ceiling. This is the most critical condition since the pitch-jet force is larger in proportion to the weight when the airplane is hovering at any lower altitude. The controllability of the full-scale airplane might be somewhat better than is implied by these results because the pitching moment of inertia of the model was about 50 percent higher in proportion to the weight than that of the airplane.

In hovering with a pitch-jet reaction control of ±4.2 percent of the model weight, the model could be trimmed with sufficient margin for control for steady flight in still air for a longitudinal center-of-gravity range from more than 12 percent chord forward of the wing pivot to 5 percent chord behind the pivot. It would have been too time consuming to have made tests of the ability of the pilots to stop violent motions such as an unstable pitching oscillation or gust disturbance for the many center-of-gravity positions required to establish the center-of-gravity range. These tests to determine the allowable center-of-gravity range were, therefore, made with the control power reduced from ±7.5 percent to ±4.2 percent of the model weight because, on the basis of past experience, this difference in control allows a sufficient margin for control of reasonably violent motions. The data of figure 4 show that centers of gravity for the full-scale airplane are well within the center-of-gravity range that could be trimmed in hovering. These data show that for the normal gross weight of 33,000 pounds and a wing incidence of $94\frac{1}{2}^{\circ}$, the center of gravity would be at 1.5 percent chord forward of the pivot and that for the minimum flying weight of 27,278 pounds and a wing incidence of $94\frac{1}{2}^{\circ}$, the center of gravity would be at 3.5 percent chord behind the pivot.

Rolling motions.- The uncontrolled rolling motions of the model in hovering flight were unstable oscillations with a period of about 4.5 seconds and a time to double the amplitude of about 1.3 seconds. In spite of this instability, the model could be flown smoothly with the roll control available (travel of $\pm 1\frac{1}{2}^{\circ}$ differential-propeller pitch) when the oscillation was not permitted to build up any appreciable amplitude before corrective control was applied.

When the rolling oscillations were allowed to build up to a modest amplitude, the pilot could not always regain control of the model. Figure 7(a) shows oscillations from which the pilot was unable to regain control of the model, and figure 7(b) shows cases in which the pilot was able to stop the oscillation. Inspection of these oscillations indicated that the amplitude of the oscillations from which the pilot had been unable to recover was not nearly as large as the amplitudes which had been permissible in other VTOL models of the same general type. Although it seems certain that the full-scale airplane will have undesirably weak roll control in hovering flight, it is difficult to interpret these results quantitatively in terms of the airplane because of a number of departures from dynamic scaling which tended to have compensating effects, as is explained next.

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Since the rolling moment of inertia of the model was considerably higher than the scaled-down value for the airplane, the control travels on the model were adjusted to give the correct scaled-down airplane rolling acceleration. Full roll-control deflection for the model was $1\frac{1}{2}^{\circ}$ of differential change in pitch of the rear elements of the dual-rotation propellers from a mean pitch of 10° at the 0.75 radius station. This deflection gave a rolling moment of ± 10.7 foot-pounds and a rolling acceleration of 1.95 radians per second per second which scales up to 0.24 radian per second per second. Full deflection for the full-scale airplane was a ± 0.75 differential change in pitch of both front and rear elements of the propellers from a mean position of 14.2° at the 0.75 radius station, which should give a rolling moment of about 26,000 foot-pounds and a rolling acceleration of 0.24 radian per second per second. It appears that the simulation of the full-scale airplane by the model was reasonably good in spite of a number of detail differences since these differences tend to be compensating. The additional weight and inertia of the model would make the oscillation more unstable, but the increased damping in roll which resulted from using a 10° propeller pitch (instead of the value of 15° used on the airplane) would tend to make the oscillation more stable. The use of increased control moment on the model offset the effect of the increased moment of inertia on rolling acceleration and also offset the effect of the increased damping in roll on the rolling velocity. The only effect of improper scaling that was not compensated at all was the effect of the increased inertia in lengthening the period of the oscillation.

In order to determine whether the controllability of the model in roll could be made satisfactory by increasing the control power, tests were made with the roll control doubled to $\pm 3^{\circ}$ of blade angle. With this

increased roll control, the controllability was excellent, probably better than was necessary. The ease and certainty with which the pilot could stop the oscillation with this amount of control is indicated by the time history of figure 8 which shows a continuous record in which the pilot first allowed the oscillation to build up and then regained control of the model three times in a period of less than 40 seconds. With the travel reduced to $\pm 2^{\circ}$, which would give about one-third more control than is expected to be available on the full-scale airplane, it was believed that the control was probably barely adequate for safe flight in reasonably smooth air. This result is illustrated by the
time history of figure 9 which shows that the pilot was able to stop L
the oscillation repeatedly, but comparison of these data with those 6
of figure 8 shows that more cycles to damp the oscillation resulted 2
than for the case of $\pm 3^{\circ}$ of blade angle. 5

<u>Yawing motions</u>.- There was, of course, no stability of yaw position in hovering flight because there was no static restoring moment in yaw. Continual use of yaw control was, therefore, required to prevent yawing as a result of random disturbances on the model. It is important to maintain a constant heading when flying the model because the model must be properly oriented with respect to the remote pilots in order for the pilots to control the model efficiently. The yaw pilot was always able to keep the model properly oriented regardless of the attitude or speed of translation that developed in the hovering flight tests. The model was easily controllable by deflecting the ailerons differentially $\pm 30^{\circ}$.

<u>Vertical motions</u>.- The model had positive rate-of-climb stability because of the pronounced inverse variation of the thrust of the propellers with axial speed. This rate-of-climb stability tended to offset the effect of a time lag in the thrust control sufficiently that the model could be maintained at a given height fairly easily.

Take-Offs and Landings

With the wing tilted up to an incidence of $94\frac{1}{2}^{\circ}$ relative to the bottom of the fuselage (thrust line vertical), the model rolled backward on take-off because of the rearward lift on the wing which was at $4\frac{1}{2}^{\circ}$ of incidence relative to the thrust line. The wheels were locked in an effort to eliminate the tendency to roll backward, but the model pitched up on take-off. If the pilot held down-elevator on take-off in addition to locking the wheels, the pitchup was eliminated but the model skidded and bounced backward. With the incidence of the wing lowered to $87\frac{1}{2}^{\circ}$ the model took off straight up, even with the wheels free.

It was found in the landing tests that there was no noticeable reduction in the control effectiveness when the model approached the ground. Landings could be performed satisfactorily with the wing incidence at either $87\frac{1}{2}^{\circ}$ or $94\frac{1}{2}^{\circ}$. With the wing incidence set at $87\frac{1}{2}^{\circ}$ there was a slight nose-down change in trim as the model approached the ground. With the wing incidence set at $94\frac{1}{2}^{\circ}$ the model had to be flown a few degrees nose down to prevent a rearward drift, therefore, the nose wheel touched down first. The model did not have vertical-position stability except when it was very near the ground where a strong favorable cushioning effect was experienced. With this inherent stability in the model, the power operator found that he could make landings easily by setting and holding the power for a slow descent since the model would slow down and stop descending as it neared the ground. The power operator could then reduce the power at his convenience and the model settled gently to the ground.

There was a progressive improvement in the stability of the pitching oscillation as the model neared the ground. The pitching oscillation was less unstable when the model was hovering with the wheels approximately 10 inches above the ground than when hovering out of the range of ground effect and was about neutrally stable when the model was hovering at a height of about 4 inches above the ground. The model was quite stable at a height of about 2 inches, and no pitch control was required to hold the model steady.

Transition Flight

Pitching motions.- The most noticeable longitudinal characteristic of the model with either the short or the long wing was that the model developed a large nose-up pitching moment when starting through transition at wing incidences somewhere between 90° and 60°. This change in trim with speed and wing incidence severely limited the range of center-of-gravity positions for which it was possible to perform the transition successfully. With the pitch-jet force of ± 7.5 percent of the model weight, the model with the short wing could be flown through the transition easily with a fuselage angle of attack and a tail incidence of 0° for a range of center-of-gravity positions from 7 percent chord forward of the wing pivot to directly below the pivot. The forward end of the center-of-gravity range was not a limiting condition but was determined by the fact that the 7-percent-chord center-of-gravity location appeared to be well forward of the design center-of-gravity range of the airplane. The rearward end of the center-of-gravity range (directly below the pivot) was limited by the inability of the pilot to trim the large nose-up pitching moment encountered at low forward speeds or high wing incidences with the pitch control available.

A study of the effect of fuselage angle of attack on the longitudinal-trim problem was made with a pitch-jet force of ±7.5 percent of the model weight. With the center of gravity still located directly below the pivot, it was found that the nose-up pitching moments were even greater with the fuselage in a 10° nose-down attitude than with the fuselage level. With the fuselage in the 10° nose-up attitude, the longitudinal-trim problem was greatly relieved. To determine the rearward center-of-gravity limit of the model when flown with the fuselage in the 10° nose-up attitude, the center of gravity was moved back progressively from a position directly below the wing pivot. The most rearward center-of-gravity position at which transition was made was at 5 percent chord behind the pivot. On the basis of the foregoing results it seems that with the short wing the full-scale airplane should be able to perform satisfactorily slow constant-altitude transition with a fuselage attitude of about 10° for the most adverse flight condition, which would be with a pitch-jet force of ±2,070 pounds (rated at maximum altitude of 10,000 feet), and the lightweight condition of 27,278 pounds, in which case the center of gravity would be at 3.5 percent chord behind the wing pivot.

In order to determine the possible improvement in the rearward center-of-gravity limit by increased pitch-jet force corresponding to sea-level conditions, transitions of the short-wing model were made with the pitch-jet force increased to ±9.1 percent of the model weight. It was found that with this increased control power the most rearward center-of-gravity location with which transition could be made successfully with the fuselage level was moved back from directly below the pivot to 7 percent chord behind the pivot. A similar 7-percent-chord improvement in the allowable center-of-gravity range presumably could be obtained for other conditions such as a positive fuselage angle of attack.

The long-wing configuration was flown with the pitch-jet force of ±7.5 percent of the model weight and a tail incidence of 0°. With the fuselage level the model could be flown easily with the center of gravity at 5 percent and 2 percent chord forward of the pivot. The center-of-gravity location of 5 percent chord forward of the pivot was not a limiting condition on the forward end of the center-of-gravity range since a large amount of residual nose-down pitch trim control was available at this condition to permit flying the model with the center of gravity located still farther forward. This model configuration could not be flown with the center of gravity located directly below the pivot, but, since this condition could be flown with the short wing, it appears that the long wing must aggravate the nose-up pitching-moment problem at low forward speeds. An increase in the fuselage angle of attack to 10° made possible successful flights of the model with the center of gravity located directly below the pivot. No attempt was made to fly with a more rearward center of gravity in the 10° attitude.

Rolling motions.- Roll control during transition flight is the most complex of the controls since the differential-propeller pitch and the ailerons interchange their functions between rolling and yawing moments as the wing tilts. With the full-scale airplane, a system for phasing the differential-propeller pitch out of and the ailerons into the roll-control circuit, as a function of wing incidence, is used to accomplish a smooth changeover from one control in hovering to the other in forward flight with the object of providing pure rolling moments through the transition. The model was not provided with a similar system for phasing one control out and the other in since, at the time the model was designed, no aerodynamic information was available on which to base the design of such a system. The technique generally used for roll control in transition with the model was to use only the differential-propeller pitch for roll control until the pilot saw that he was getting too much favorable yaw from the propellers. At that time, which occurred at an airspeed of approximately 24 knots and a wing angle of attack of about 51°, the pilot switched out the differential-propeller-pitch control and switched the ailerons and rudder into the roll-control circuit. The amount of roll control provided by $\pm 1\frac{1}{2}^{\circ}$ differential-propeller pitch was sufficient to permit the model to be flown smoothly and easily during these tests.

A few flights were made satisfactorily with another system of roll control where the pilot left the differential-propeller-pitch control in the circuit throughout the transition and switched the ailerons in when he saw he was getting too much favorable yaw from the propellers. When the ailerons were used in conjunction with the differential-propeller pitch for roll control, the adverse yawing moments of the ailerons tended to offset the excessive favorable yawing moments produced by the change in propeller pitch, whereas the rolling moments of the ailerons tended to augment the rolling moments produced by the propeller-pitch change. The fact that the propeller-pitch change gave reasonably good roll control at low angles of wing incidence results from the change in velocity over the part of the wing in the propeller slipstream. For example, an increase in the pitch of the propeller on one wing increases the velocity over the wing behind the propeller and thereby causes an increase in the lift and drag of that part of the wing. The increase in lift gives a sizeable rolling moment, whereas the increase in drag tends to offset the increase in thrust of the propeller.

Flights were made with the long-wing configuration in which the airspeed was held constant at 22, 29, 36, and 44 knots. When scaled up for the full-scale airplane, these airspeeds would be 62, 82, 103, and 125 knots, respectively. Various combinations of rudder, ailerons, and differential-propeller pitch were tried for roll control. Although these flights were made with the long-wing configuration, these roll-control results are believed to apply also to the short-wing configuration, especially at the higher wing incidences, since the tip extensions on the long wing were outside the propeller slipstream and added only a small increment in rolling inertia.

With the airspeeds held constant at 22 knots (wing angle of attack about 53°) good roll control was obtained by using only the differential-propeller pitch control. At 29 knots (wing angle of attack about 43°) control with the propeller pitch alone was not satisfactory because of excessive favorable yawing moments due to the control. At this speed, control with the propellers and ailerons combined was reasonably good but slightly less desirable than the combined rudder and aileron control. Roll control with ailerons alone at the speed of 29 knots was undesirable since this control gave excessive adverse yawing moments which made the model wallow excessively. At 36 knots (wing angle of attack about 32°), however, this ailerons-alone control seemed adequate. The model was not flyable with the rudder-alone control at any of these test speeds. In summary, it seemed that roll control with propeller pitch alone was satisfactory at speeds up to about 24 knots and that combined rudder and ailerons control was the best control at the airspeeds above 24 knots.

Yawing motions.- Up to an airspeed of about 14 knots the model could be flown smoothly and easily although some yaw control was required. At higher airspeeds, the directional stability was adequate to permit the model to fly satisfactorily without the use of yaw control except when the rudder was used in combination with the ailerons to counteract the adverse yawing moments of the ailerons.

Rearward and Sideward Flight

Rearward flight was accomplished by flying the model backwards in the tunnel. The model was easily controllable as the airspeed was increased from 0 to about 19 knots (55 knots full-scale) at which speed the test was concluded since it was thought that the speed range more than covered practical limits for this condition. Since the wing could not be tilted beyond an incidence of $94\frac{1}{2}^{\circ}$, the model required high nose-up attitudes (on the order of 40°) to hover at the higher test speeds.

Sideward flight was accomplished by flying the model with the right wing pointed into the wind in the tunnel. The model was controllable in roll up to an airspeed of 9 knots (25 knots full-scale), at which speed the roll control became inadequate to hold a trimmed condition. The differential-propeller-pitch roll control was set with a travel of $\pm 1\frac{1}{2}^{\circ}$ starting from a mean pitch of 10° at the 0.75 radius station. The trimmed pitch on the propellers at the end of the sideward flights measured 13° on the left rear propeller elements and 7° on the right rear propeller elements with the control travel still $\pm 1\frac{1}{2}^{\circ}$ except that the blade pitch was mechanically limited to a maximum of 13°. These control deflections represented more than twice the amount of control available on the full-scale airplane, so it seems that the airplane would be limited to hovering in low sidewinds.

CONCLUSIONS

The following conclusions are drawn from an investigation of the stability and control characteristics of a 1/8-scale flying model of a tilt-wing vertical-take-off-and-landing airplane:

1. In hovering flight the model had an unstable pitching oscillation with a period of about 4.6 seconds and a time to double the amplitude of about 1.1 seconds. With a pitch-jet reaction-control force of ±7.5 percent of the model weight, the pilot could stop this oscillation easily, even after the oscillation had been allowed to build up to a large amplitude. The full-scale airplane should be easily controllable with this amount of pitch control.

2. The uncontrolled rolling motions of the model in hovering flight were unstable oscillations with a period of about 4.5 seconds and a time to double the amplitude of about 1.3 seconds. When the full-scale-airplane roll control was simulated as closely as possible, the model could be flown smoothly if the oscillation was not permitted to build up, but the pilot could not always regain control of the model if the oscillation built up to a modest amplitude. It was thus concluded that this amount of control, which was obtained with $\pm 1\frac{1}{2}^{\circ}$ of differential pitch of the rear elements of the dual-rotation propellers, was undesirably weak. It was found that when the roll control was doubled to ±3° of blade angle, the roll control was excellent, and with the travel reduced to ±2° it was believed that the control was probably adequate for safe flight of the airplane in relatively smooth air. It was found that in order to trim the model in a crosswind of 9 knots (represents 25 knots full scale) an additional ±3° of blade angle was required for roll control.

3. In hovering flight the yawing motions of the model were easily controllable by deflecting the ailerons differentially ±30°. The model could always be kept properly oriented regardless of the attitude or speed of transition that developed in the hovering flight tests.

4. Take-offs and landings were easy to perform. The model had a strong favorable cushioning effect when nearing the ground. As the model neared the ground there was a progressive improvement in the stability of the pitching oscillation from unstable to stable.

5. In the transition from hovering to forward flight with either the long or the short wing, the model experienced a large nose-up pitching moment at angles of wing incidence somewhere between 90° and 60° which severely limited the allowable center-of-gravity range. This pitching moment could be markedly relieved by allowing the model to fly with the fuselage in a modest nose-up attitude. With the short wing, the full-scale airplane should be able to perform satisfactorily slow constant-altitude transitions with a fuselage attitude of about 10° for the most adverse flight condition (flight at 10,000 feet altitude in the lightweight condition of 27,278 pounds, in which case the center of gravity would be 3.5 percent chord behind the wing pivot).

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6. Rolling motions of the model could be controlled easily throughout the transition range by either of two roll-control systems used. One roll-control system used only the differential-propeller pitch until the pilot saw he was getting too much favorable yaw from the propellers, which occurred at an airspeed of approximately 24 knots, and then the pilot switched out the differential-propeller-pitch control and switched the ailerons and rudder into the roll-control circuit. The second roll-control system used the differential-propeller-pitch control in the circuit throughout the transition, and the pilot switched the ailerons in when he saw he was getting too much favorable yaw from the propellers.

7. The yawing motions of the model were easily controllable in the transition range up to an airspeed of about 14 knots, and at the higher airspeeds in transition the pilot did not have to give any corrective yaw control except that the rudder had to be used in conjunction with the ailerons to counteract the adverse aileron yawing moments.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Field, Va., June 23, 1959.

REFERENCE

1. Tosti, Louis P.: Force-Test Investigation of the Stability and Control Characteristics of a 1/8-Scale Model of a Tilt-Wing Vertical-Take-Off-and-Landing Airplane. NASA TN D-44, 1960.

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TABLE I.- SCALED-UP GEOMETRIC CHARACTERISTICS OF MODEL

Propellers (6 blades each):	
Diameter, ft	16
Chord, ft	1.43
Total solidity	0.286
Wing:	
Area:	
Short, sq ft	528
Long, sq ft	660
Span:	
Short, ft	48
Long, ft	60
Chord, ft	11.0
Aspect ratio:	
Short	4.36
Long	5.45
Taper ratio	1.0
Airfoil section	NACA 23015
Pivot station, percent chord	34.8
Sweepback (leading edge), deg	0
Dihedral angle, deg	0
Incidence relative to propeller shaft axis, deg	4.5
Ailerons (each):	
Chord, ft	2.20
Span:	
Outboard portion, ft	6.46
Inboard portion, ft	8.41
Hinge line, percent chord	0.80
Vertical tail:	
Area, sq ft	118.2
Span, ft	14.33
Tip chord, ft	4.42
Root chord, ft	12.08
Aspect ratio	1.19
Taper ratio	0.273
Airfoil section	NACA 0009
Sweepback (leading edge), deg	22.15
Rudder (hinge line perpendicular to fuselage center line):	
Tip chord (behind hinge line), ft	1.0
Root chord (behind hinge line), ft	2.87
Span, ft	16.75
Horizontal tail:	
Area (projected), sq ft	197.75
Span (projected), ft	28.21
Tip chord, ft	4.00
Root chord, ft	10.02
Aspect ratio	4.03
Taper ratio	0.399
Airfoil section	NACA 0011
Sweepback (leading edge), deg	15.94
Dihedral angle, deg	15
Elevator (hinge line perpendicular to fuselage center line):	
Tip chord (behind hinge line), ft	1.33
Root chord (behind hinge line), ft	3.25
Span (each), ft	13.84
Overall length, ft	62.67

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TABLE II.- COMPARISON OF MASS CHARACTERISTICS OF MODEL

(SCALED-UP) AND FULL-SCALE AIRPLANE AT

A WING INCIDENCE OF 90°

	Model (scaled-up)	Full-scale airplane
Weight, lb	37,275	33,000
Rolling moment of inertia, I_X, slug-ft^2	180,900	108,790
Pitching moment of inertia, I_Y, slug-ft^2	180,500	116,150
Yawing moment of inertia, I_Z, slug-ft^2	319,400	183,350

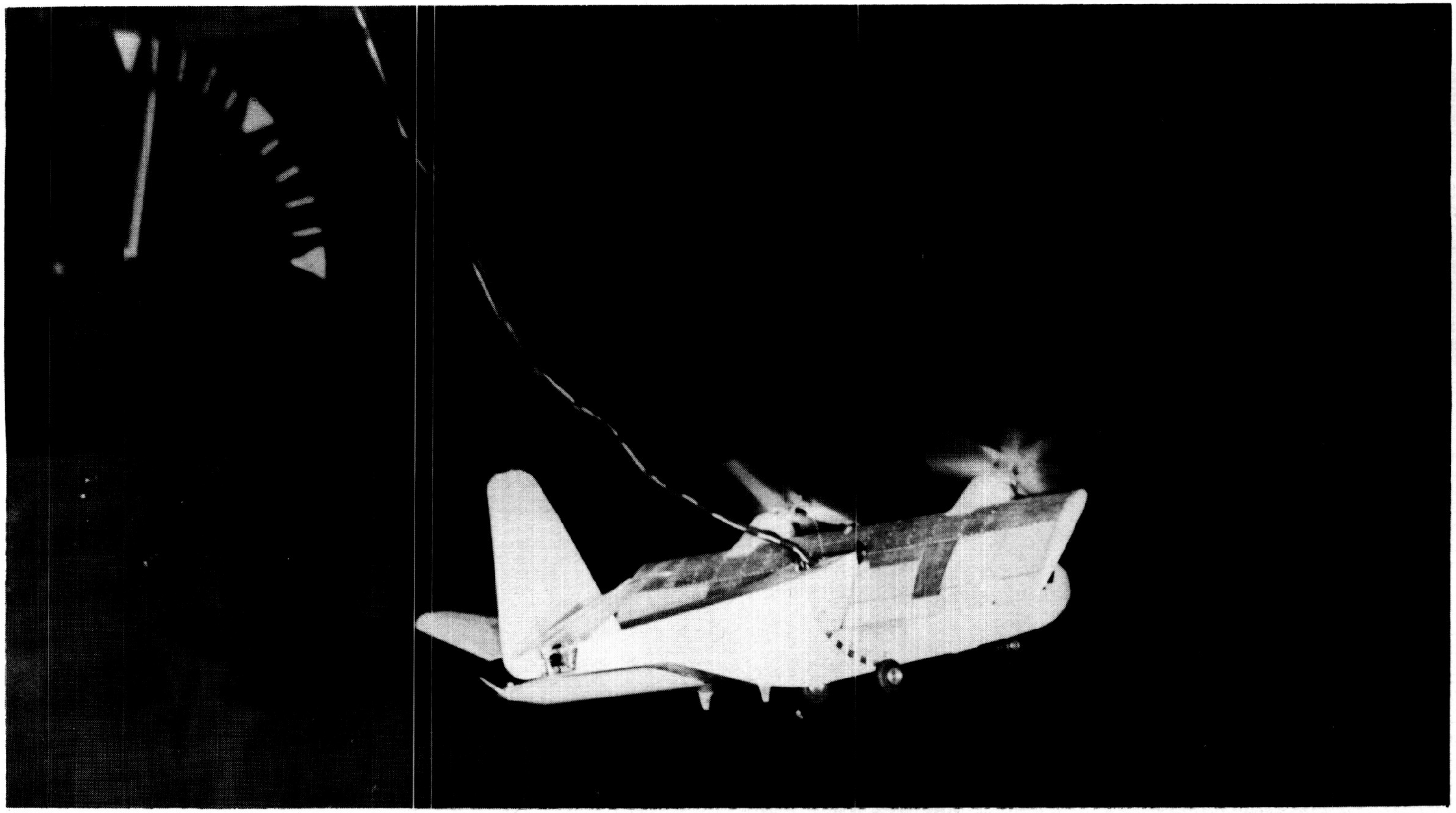

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Figure 1.- Photograph of 1/8-scale model of Hiller X-18 airplane during transition flight in Langley full-scale tunnel.

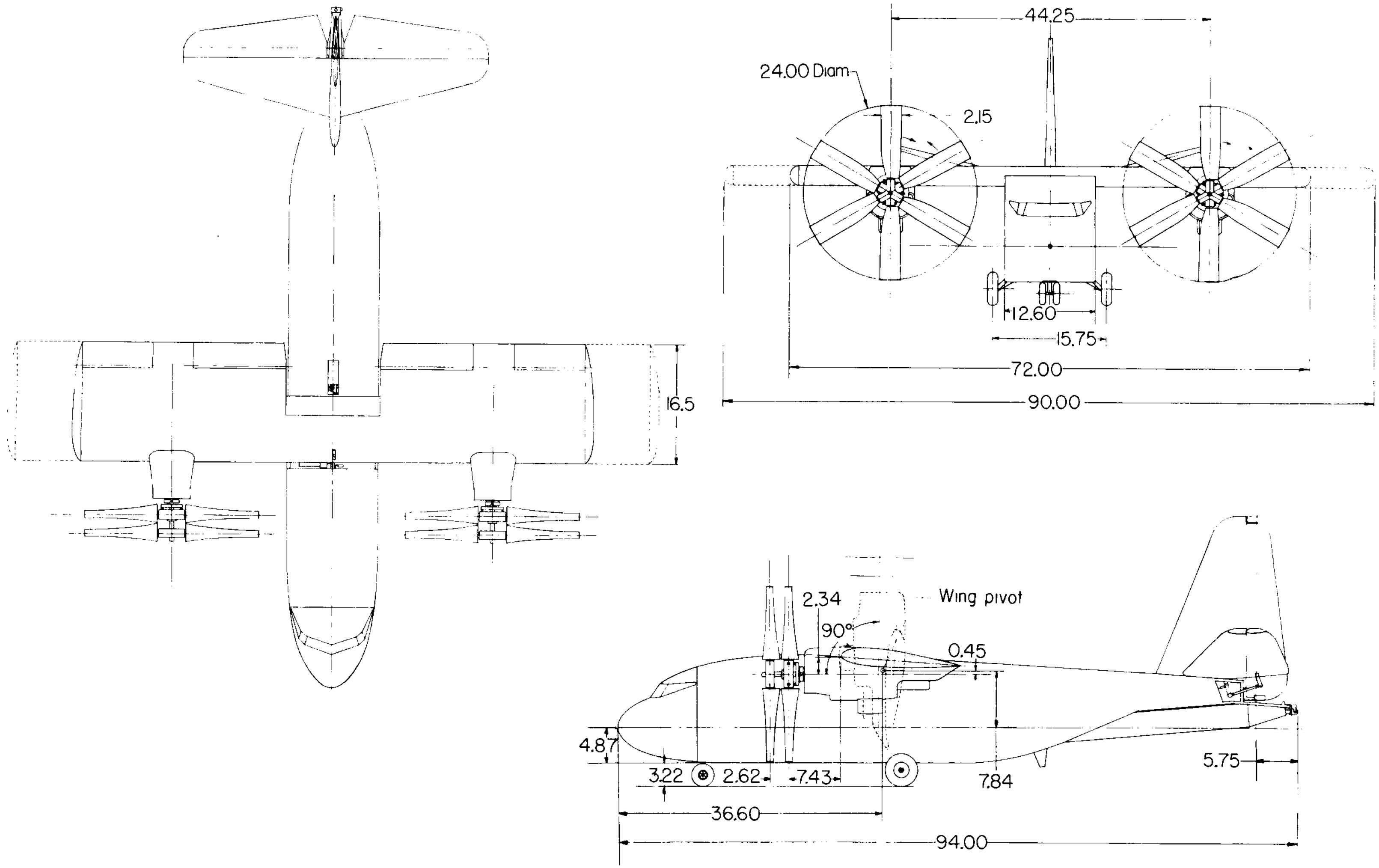

Figure 2.- Three-view sketch of model. All linear dimensions are in inches.

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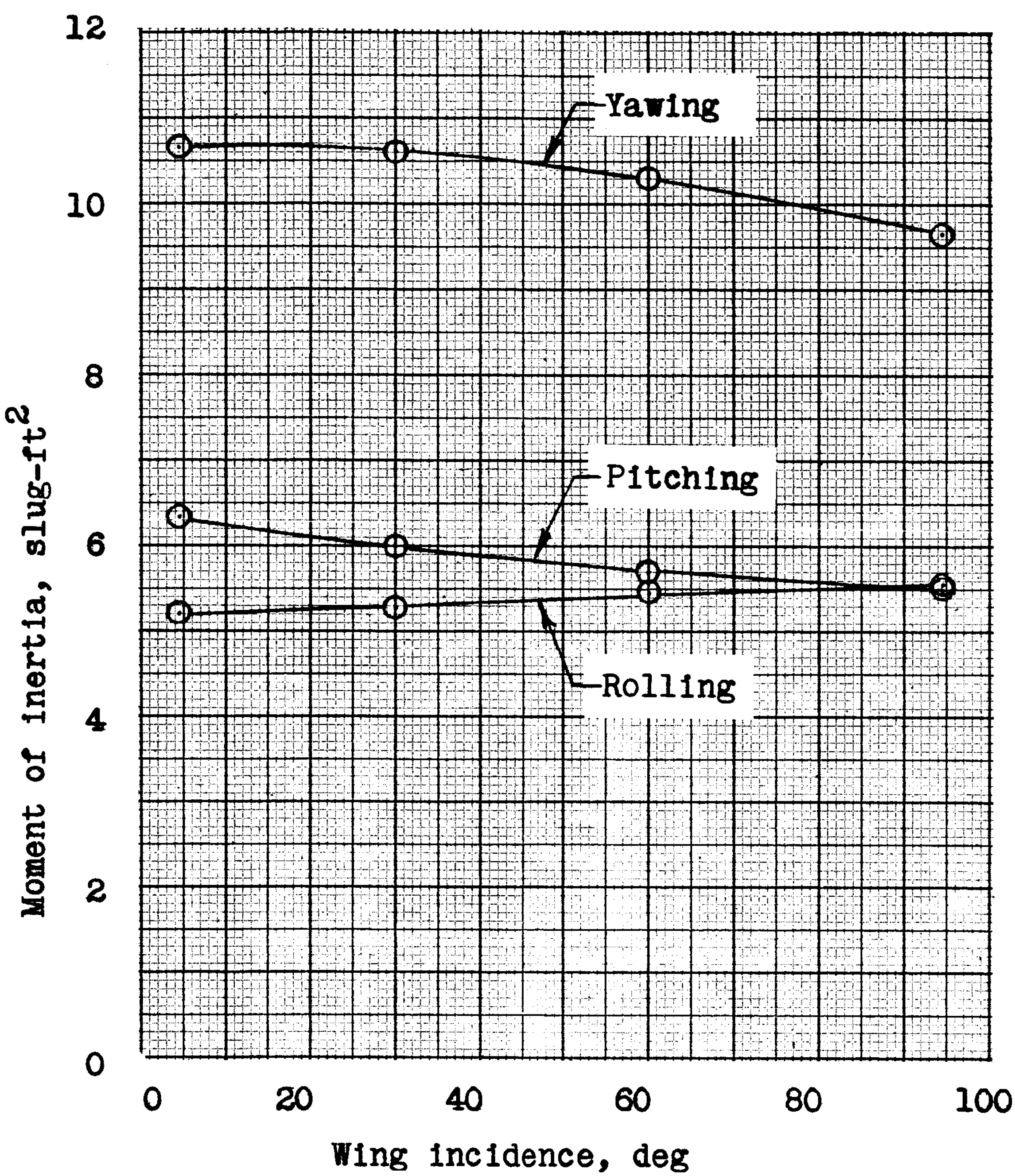

Figure 3.- Moments of inertia of model about center-of-gravity locations indicated in figure 4. Model weight, 72.8 pounds. No buoyancy, virtual mass, or entrapped air corrections.

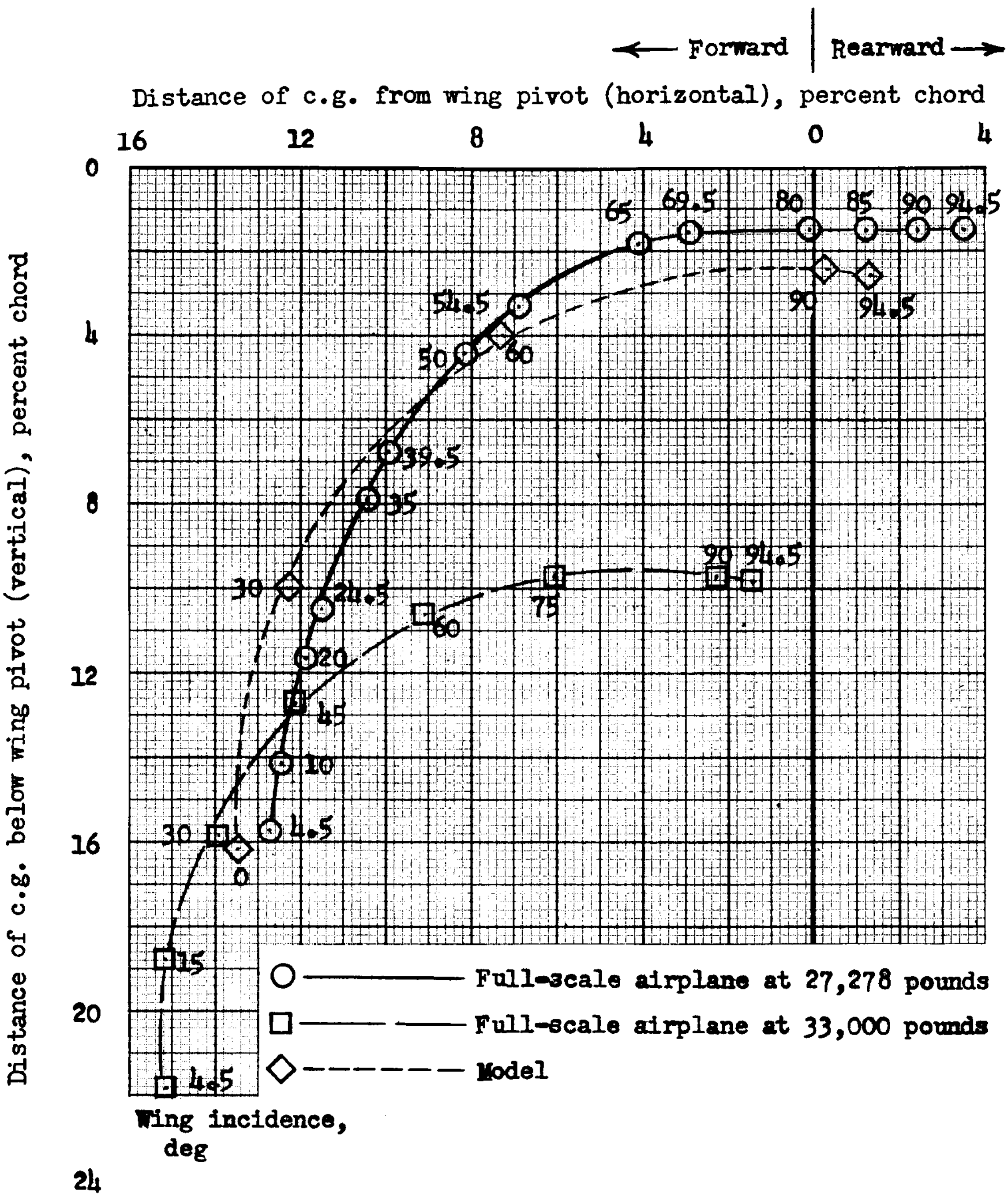

Figure 4.- Comparison of center-of-gravity locations of full-scale airplane and model at various wing incidence angles.

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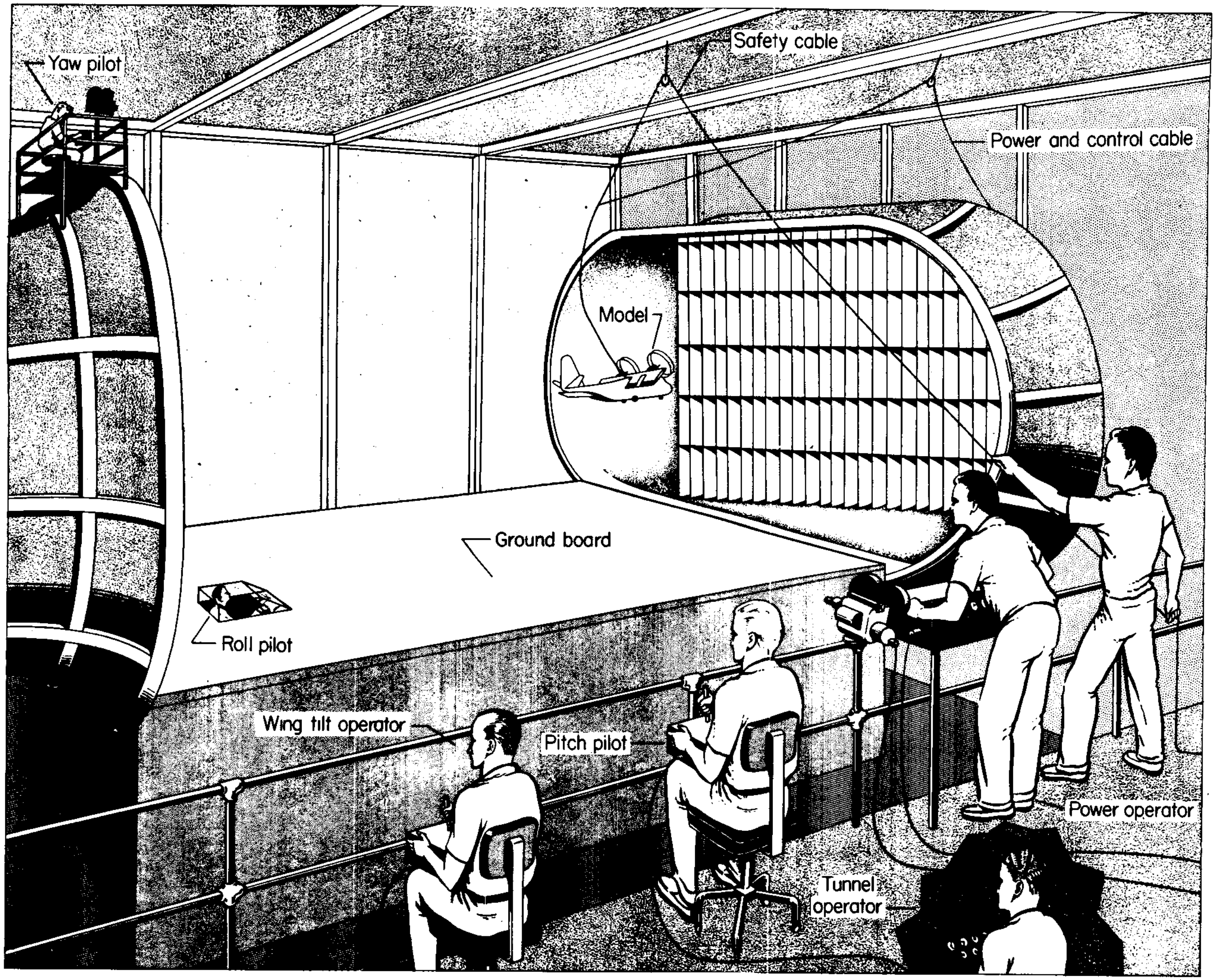
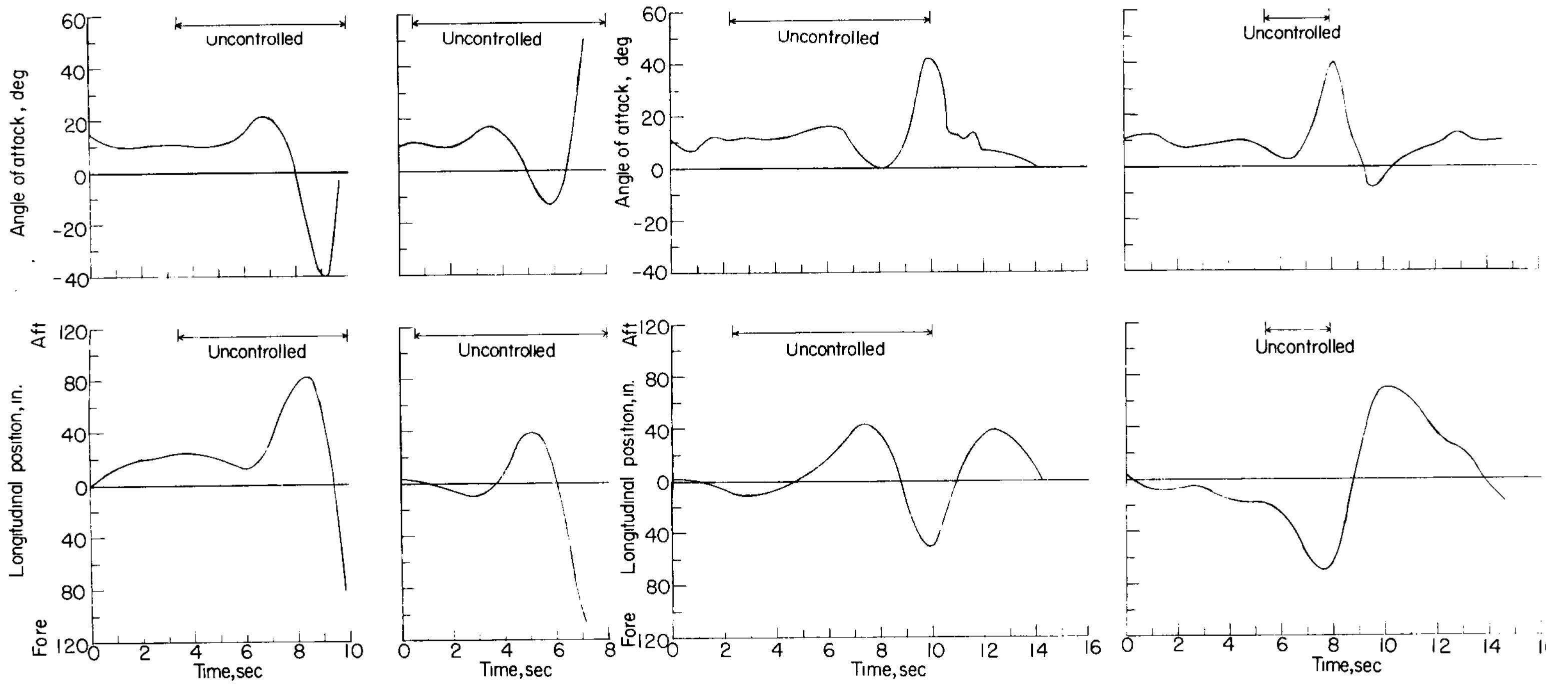


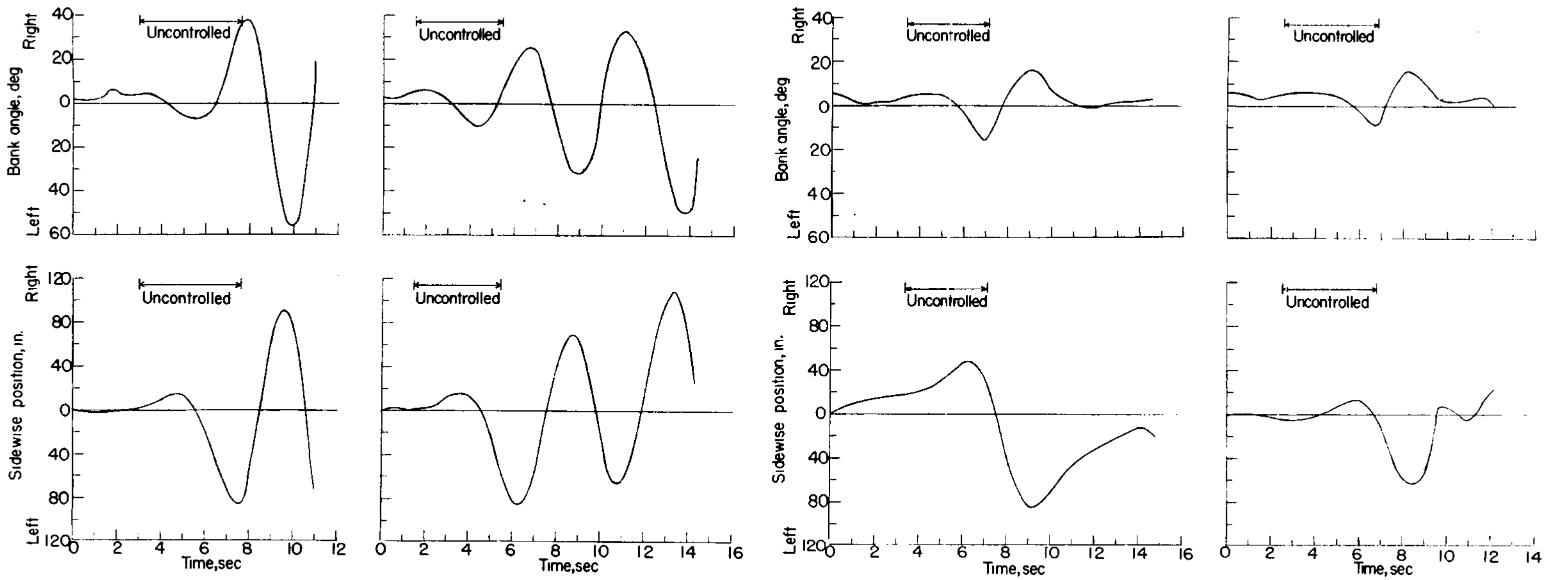
Figure 5.- Sketch of test setup for slow constant-altitude transition tests in Langley full-scale tunnel.



(a) Oscillations that pilot did not attempt to stop.

(b) Oscillations that pilot was able to stop.

Figure 6.- Pitching oscillations in hovering flight with a pitch-jet reaction-control force of ±7.5 percent of model weight. (Pilot was applying control except for periods labeled uncontrolled.)



(a) Oscillations that pilot was unable to stop.

(b) Oscillations that pilot was able to stop.

Figure 7.- Rolling oscillations in hovering flight with propeller control deflections of $\pm 1\frac{1}{2}^{\circ}$ on rear elements of each dual-rotating propeller. (Pilot was applying control except for periods labeled uncontrolled.)

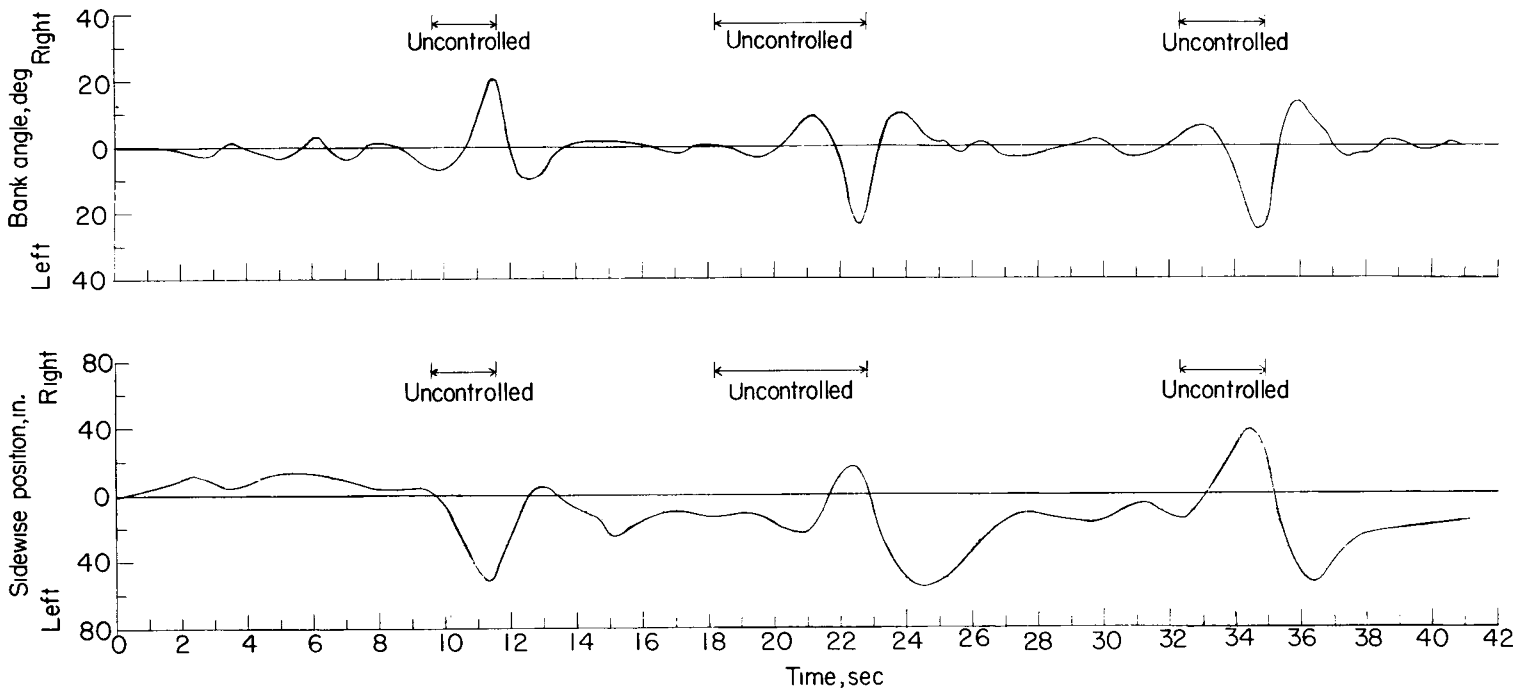


Figure 8.- Rolling oscillations in hovering flight with propeller control deflections of ±3° on rear elements of each dual-rotating propeller. (Pilot was applying control except for periods labeled uncontrolled.)

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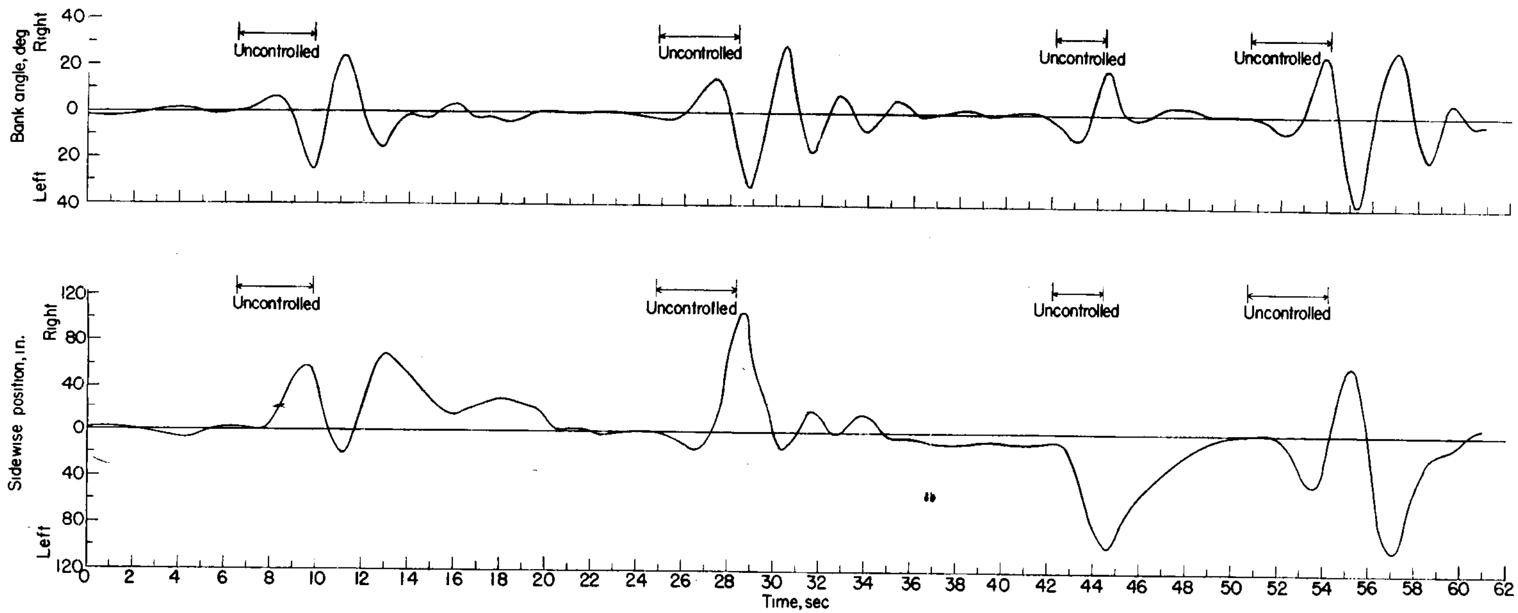

Figure 9.- Rolling oscillations in hovering flight with propeller control deflections of ±2° on rear elements of each dual-rotating propeller. (Pilot was applying control except for periods labeled uncontrolled.)